Letters to the Editor

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NOTES ON POINTS IN SOME OF THIS WEEK'S LETTERS APPEAR ON P. 247.

CORRESPONDENTS ARE INVITED TO ATTACH SIMILAR SUMMARIES TO THEIR COMMUNICATIONS.

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

ON bombarding uranium with neutrons, Fermi and collaborators[1] found that at least four radioactive substances were produced, to two of which atomic numbers larger than 92 were ascribed. Further investigations[2] demonstrated the existence of at least nine radioactive periods, six of which were assigned to elements beyond uranium, and nuclear isomerism had to be assumed in order to account for their chemical behaviour together with their genetic relations.

In making chemical assignments, it was always assumed that these radioactive bodies had atomic numbers near that of the element bombarded, since only particles with one or two charges were known to be emitted from nuclei. A body, for example, with similar properties to those of osmium was assumed to be eka-osmium ($Z = 94$) rather than osmium ($Z = 76$) or ruthenium ($Z = 44$).

Following up an observation of Curie and Savitch[3], Hahn and Strassmann[4] found that a group of at least three radioactive bodies, formed from uranium under neutron bombardment, were chemically similar to barium and, therefore, presumably isotopic with radium. Further investigation[5], however, showed that it was impossible to separate these bodies from barium (although mesothorium, an isotope of radium, was readily separated in the same experiment), so that Hahn and Strassmann were forced to conclude that *isotopes of barium* ($Z = 56$) *are formed as a consequence of the bombardment of uranium* ($Z = 92$) *with neutrons.*

At first sight, this result seems very hard to understand. The formation of elements much below uranium has been considered before, but was always rejected for physical reasons, so long as the chemical evidence was not entirely clear cut. The emission, within a short time, of a large number of charged particles may be regarded as excluded by the small penetrability of the 'Coulomb barrier', indicated by Gamov's theory of alpha decay.

On the basis, however, of present ideas about the behaviour of heavy nuclei[6], an entirely different and essentially classical picture of these new disintegration processes suggests itself. On account of their close packing and strong energy exchange, the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, such a drop may divide itself into two smaller drops.

In the discussion of the energies involved in the deformation of nuclei, the concept of surface tension of nuclear matter has been used[7] and its value has been estimated from simple considerations regarding nuclear forces. It must be remembered, however, that the surface tension of a charged droplet is diminished by its charge, and a rough estimate shows that the surface tension of nuclei, decreasing with increasing nuclear charge, may become zero for atomic numbers of the order of 100.

It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of sizes depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should gain a total kinetic energy of c. 200 Mev., as calculated from nuclear radius and charge. This amount of energy may actually be expected to be available from the difference in packing fraction between uranium and the elements in the middle of the periodic system. The whole 'fission' process can thus be described in an essentially classical way, without having to consider quantum-mechanical 'tunnel effects', which would actually be extremely small, on account of the large masses involved.

After division, the high neutron/proton ratio of uranium will tend to readjust itself by beta decay to the lower value suitable for lighter elements. Probably each part will thus give rise to a chain of disintegrations. If one of the parts is an isotope of barium[5], the other will be krypton ($Z = 92 - 56$), which might decay through rubidium, strontium and yttrium to zirconium. Perhaps one or two of the supposed barium-lanthanum-cerium chains are then actually strontium-yttrium-zirconium chains.

It is possible[5], and seems to us rather probable, that the periods which have been ascribed to elements beyond uranium are also due to light elements. From the chemical evidence, the two short periods (10 sec. and 40 sec.) so far ascribed to ^{239}U might be masurium isotopes ($Z = 43$) decaying through ruthenium, rhodium, palladium and silver into cadmium.

In all these cases it might not be necessary to assume nuclear isomerism; but the different radioactive periods belonging to the same chemical element may then be attributed to different isotopes of this element, since varying proportions of neutrons may be given to the two parts of the uranium nucleus.

By bombarding thorium with neutrons, activities are obtained which have been ascribed to radium and actinium isotopes[8]. Some of these periods are approximately equal to periods of barium and lanthanum isotopes[5] resulting from the bombardment of uranium. We should therefore like to suggest that these periods are due to a 'fission' of thorium which is like that of uranium and results partly in the same products. Of course, it would be especially interesting if one could obtain one of these products from a light element, for example, by means of neutron capture.

It might be mentioned that the body with half-life 24 min.[2] which was chemically identified with uranium is probably really ^{239}U, and goes over into an eka-rhenium which appears inactive but may decay slowly, probably with emission of alpha particles. (From inspection of the natural radioactive elements, ^{239}U cannot be expected to give more than one or two beta decays; the long chain of observed decays has always puzzled us.) The formation of this body is a typical resonance process[9]; the compound state must have a life-time a million times longer than the time it would take the nucleus to divide itself. Perhaps this state corresponds to some highly symmetrical type of motion of nuclear matter which does not favour 'fission' of the nucleus.

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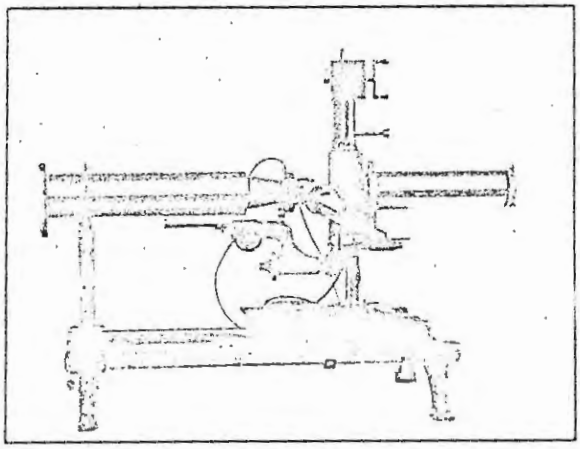
Jan. 16.

[1] Fermi, E., Amaldi, F., d'Agostino, O., Rasetti, F., and Segrè, E. *Proc. Roy. Soc.*, A, 146, 483 (1934).
[2] See Meitner, L., Hahn, O., and Strassmann, F., *Z. Phys.*, 106, 249 (1937).
[3] Curie, I., and Savitch, P., *C.R.*, 208, 906, 1643 (1938).
[4] Hahn, O., and Strassmann, F., *Naturwiss.*, 26, 756 (1938).
[5] Hahn, O., and Strassmann, F., *Naturwiss.*, 27, 11 (1939).
[6] Bohr, N., NATURE, 137, 344, 351 (1936).
[7] Bohr, N., and Kalckar, F., *Kgl. Danske Vid. Selskab, Math. Phys. Medd.*, 14, Nr. 10 (1937).
[8] See Meitner, L., Strassmann, F., and Hahn, O., *Z. Phys.*, 109, 538 (1938).
[9] Bethe, A. H., and Placzek, G., *Phys. Rev.*, 51, 450 (1937).

A Novel Thermostat

IT is often necessary to maintain an apparatus at a constant temperature. This may be done by immersing it in a circulating liquid maintained at a constant temperature by a thermostat, or by jacketing



TEMPERATURE-CONTROLLED APPARATUS.

it with alternate shells of thermally conducting and insulating materials heated to the selected temperature by means of an internal electric heater. These methods have the disadvantages that the thermostatic system makes the apparatus less accessible, the control of the temperature to within a narrow range requires some complication in the whole system, and it is difficult to prevent 'hunting'.

In a measurement which we are making of the electronic charge, it is necessary to maintain the temperature of the air, in which an oil drop moves, uniform and constant so that it has no motion due to convection. As a convenient solution of this problem has been found which seems capable of many applications, it is described here.

A resistance thermometer is formed by winding a single layer coil of copper wire around and in good thermal contact with the microscope condenser which forms part of the apparatus the temperature of which is under control. (In the accompanying illustration the condenser tube is on the right.) This coil forms one arm of a Wheatstone bridge, the other arms being of manganin resistances. Any change in temperature of the apparatus deflects the light spot of the galvanometer connected to this bridge, and for one direction of deflection the spot falls on a photo-electric cell, which operates a polarized relay, which in turn puts off two 30-watt lamps placed on opposite sides of the apparatus. The amplification of the galvanometer current by the photo-electric cell is 10^6, and including the relay about 10^7.

The bridge is adjusted to be balanced at a temperature a few degrees above the maximum temperature to which the room rises during a day. The lamps flash on and off every few seconds and maintain the temperature of the external surface of the apparatus constant to about 0·002° C. After the thermostat has been in operation for an hour, we have not been able to detect, by means of a thermo-couple, any change of temperature inside the apparatus.

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V. D. HOPPER.

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Dec. 9.

Limitations on the Modern Tensor Scheme of Relativity

IT does not appear to have been noticed by anybody that the tensor scheme of relativity is incompetent by itself to include relations of chirality, to use Lord Kelvin's term. For it is developed from a pure Riemannian geometry, as based solely on the use of an ideal mobile a-chiral linear measuring rule. The meaning of relativity has, of course, always been that knowledge consists of the relations of one system to another, especially when one type of system of high simplicity, such as the linear measuring rule, is taken as the standard of comparison for all others. This significance of the chiral property, which is the difference between a chiral system and its mirror-image, for example, between a right-hand glove and a left-hand, goes back to Kant's early writings, and remained fundamental in his trains of thought in relation to space and time; later, in the more amateur hands of Pasteur, it created a fundamental science. Chiral systems can be compared completely only with chiral systems. The frame of reference for a chiral system must itself have chiral property; for example, to be effective, the mobile measuring rod of Einstein would require to possess a screw structure essential to it. When Newton explained how he could tell by experiment

Isotopes of the Alkaline Earth Metals from Uranium

DURING the last two years, the bombardment of uranium by neutrons has led to some striking results, due primarily to the combined efforts of Prof. O. Hahn, L. Meitner and F. Strassmann, working in the Kaiser Wilhelm Institute of Chemistry in Berlin-Dahlem. In addition to *three* artificial isotopes of uranium, they have succeeded in establishing the existence of *six* trans-uranium elements of atomic numbers 93–96, and the existence of a seventh trans-uranium element (half-value period = 60 days) is indicated.

In similar experiments, I. Curie and P. Savitch obtained evidence of the production of a substance with a half-value period of 3½ hours. The identity of this substance is uncertain, and although the authors have considered several possibilities, none of them is very satisfactory. Recent experiments on the chemical properties of the trans-uranium elements have led O. Hahn and F. Strassmann (*Naturwissenschaften*, 26, 755, Nov. 18, 1938; and 27, 11, Jan. 6, 1939) to look for this substance (half-value period = 3½ hours), and they have been successful in obtaining it by the same methods as those used by the French workers. Their investigations have led to remarkable results which are summarized in what follows.

The bombardment of uranium with neutrons apparently resulted in the production of *four isomeric isotopes of 'radium'*, which must have arisen by two successive α-ray transformations via thorium. These four 'radium' isotopes omit β-rays and yield four isomeric isotopes of 'actinium', which, in their turn, by further emission of β-rays, presumably give rise to four isotopes of 'thorium', but details of these last products are still incompletely known. The results so far obtained may be represented provisionally by the following scheme, in which the nature of the radiations emitted and the revised half-value periods of the new products are indicated.

$$^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{92}U \xrightarrow{\alpha} {}^{235}_{90}Th \xrightarrow{\alpha} \begin{cases} \text{'Ra}_{\text{i}}\text{'} ? \xrightarrow[<1\text{ m.}]{\beta} \text{'Ac}_{\text{i}}\text{'} \xrightarrow[<30\text{ m.}]{\beta} \text{'Th'} ? \\ \text{'Ra}_{\text{ii}}\text{'} \xrightarrow[14\pm2\text{ m.}]{\beta} \text{'Ac}_{\text{ii}}\text{'} \xrightarrow[\text{c. 2·5h.}]{\beta} \text{'Th'} ? \\ \text{'Ra}_{\text{iii}}\text{'} \xrightarrow[80\pm6\text{m.}]{\beta} \text{'Ac}_{\text{iii}}\text{'} \xrightarrow[\text{sev. days?}]{\beta} \text{'Th'} ? \\ \text{'Ra}_{\text{iv}}\text{'} \xrightarrow[250\text{-}300\text{h.}]{\beta} \text{'Ac}_{\text{iv}}\text{'} \xrightarrow[<40\text{ h.}]{\beta} \text{'Th'} ? \end{cases}$$

Should this scheme adequately represent the facts, these twelve new substances should have atomic weights of value 231, and since a natural thorium isotope (UY) of atomic weight 231 and half-value period 25 hours is already known, it will be of interest to investigate whether one of the four 'thorium' isotopes is identical with UY.

Hahn and Strassmann believe that the substance found by Curie and Savitch is a mixture of the above-mentioned isotopes, each of which has been individually detected and chemically examined. Moreover, the properties of such a mixture would agree with those of the substance detected by the latter authors, who suspect that their substance also contains others of longer life, but of unknown genesis.

An interesting feature of this work is that the production of the new isotopes is enhanced by the use of *slow* neutrons, and the α-particle disintegrations indicated in the earlier stages of the process are believed to be the first instances of α-particle emission effected by *slow* neutrons. It is, of course, possible that the quadruplicity of isotopes resulting from the bombardment of uranium by neutrons takes place in $^{239}_{92}U$, as in the case of the trans-uranium elements, and the intermediate 'thorium' isotope $^{235}_{90}Th$ may also possess four half-value periods.

In the second of their publications mentioned above, Hahn and Strassmann give particulars of the chemical methods employed in establishing their results, as well as a number of activity curves from which some of the half-value periods have been derived. In order to establish beyond question the chemical nature of the products they have designated 'radium' isotopes, which were separated with barium, the authors carried out fractional crystallizations and precipitations with the active barium salts, by the method used for altering the concentration of radium in salts of barium containing radium.

As is well known, crystals richer in radium can be obtained by fractional crystallization of the chloride, bromide or chromate of barium, when it contains radium. In experiments on these lines, carried out by Hahn and Strassmann with their active barium preparations from which disintegration products had been removed, negative results were always obtained, that is, the activity was uniformly distributed amongst the various barium fractions, whereas control experiments with barium containing the radium isotopes ThX and $MsTh_1$ yielded results conforming to those obtained when the barium contains ordinary radium. In a further experiment, in which 'Ra$_{\text{iv}}$' and $MsTh_1$ were mixed with barium and then subjected to fractional crystallization, only the $MsTh_1$ was concentrated in the process.

The authors conclude from these results that their 'radium' isotopes have the properties of barium, and that, from the chemical point of view, other elements being excluded, these active substances must be regarded as consisting not of radium but of *barium*. This conclusion has been confirmed by further indicator experiments, according to a personal communication from one of the authors (O.H.).

Hahn and Strassmann have also subjected a mixture of their 'Ac$_{\text{ii}}$' and the actinium isotope $MsTh_2$ with lanthanum oxalate to fractionation from a nitric acid solution. At the end of the process a gain in concentration of $MsTh_2$ was achieved, but no increase in the concentration of 'Ac$_{\text{ii}}$' was noted. From this they conclude that the substances generated by β-ray emission from their alkaline-earth products are not isotopes of actinium, a conclusion which agrees with that of Curie and Savitch for their composite product of half-value period 3½ hours. In all probability they will prove to be isotopes of *lanthanum*. The products designated 'Th' in the above scheme of disintegration, which constitute the final members of the series

derived from the 'Ac-La' preparations, have not yet been tested for their identity with *cerium*.

On the strength of the chemical evidence, it is difficult to avoid the conclusion that the elements denoted by the symbol 'Ra' in the above-mentioned disintegration scheme should in reality be designated 'Ba', and so far as the evidence has gone it seems probable that the succeeding elements 'Ac' and 'Th' will prove to be 'La' and 'Ce' respectively. It is as though, at some stage in the process resulting from the bombardment of uranium by neutrons, a 'collapse' of the nucleus occurs, giving rise to the four active isomeric alkaline-earth elements and the succeeding 'lanthanum' and 'cerium' products. The investigations are being continued. R. W. L.

Subspecies and Varieties

A DISCUSSION dealing with subspecies and varieties was held at the meeting of the Linnean Society on February 2. This discussion had been arranged at the request of the Association for the Study of Systematics in Relation to General Biology in order to obtain information as to the views and principles governing the practice of systematists in various groups of animals and plants. It was apparent from the discussion that systematists are generally dissatisfied with the existing state of affairs. As was to be expected, little or no attention is paid to infra-specific categories in the less-known groups of both plant and animal kingdoms; but where the broader taxonomic outlines are well understood there is considerable divergence in systematic practices according to the amount of genetical, cytological and ecological work that has been done. In vertebrates, only a single infra-specific category, the 'subspecies', is generally recognized, but in entomology and botany there are others. How many there may be and their status in the taxonomic scheme are matters of dispute, and there is a disturbing confusion in the terminology applied to them. In this connexion, it may be mentioned that the Association is compiling a list of the various terms which have been used. Almost all the speakers stressed the need for more experimental work from the genetical, cytological, physiological and ecological aspects.

In opening the discussion, Mr. M. A. C. Hinton described the practice of mammalogists, who, in recent years, have used the term 'subspecies' to express stages or trends in geographical variation; they are sections of what Dr. Julian Huxley has called 'clines' (NATURE, 142, 219; 1938). One principle generally accepted is that no two races of the same species can ever be found on the same ground, though exceptionally two such forms may meet after very different histories and journeys and continue to exist side by side without fusing. The principle that, unless intergradation can be demonstrated, differences, however trivial, indicate specific separation, has some theoretical support. In practice, however, it has disadvantages, especially in dealing with insular forms, and tends to mask that most interesting and instructive phenomenon, discontinuous distribution.

The definition of subspecies is an essential part of any intensive analysis of the facts of variation and distribution, and is particularly valuable in palæontology, by preventing loose identifications and consequent faulty geological deductions. It is hoped soon to commence large-scale experiments to test the values and permanence of subspecific characters and to obtain more definite information on subjects concerning which surmise alone is at present possible.

Dr. W. B. Turrill emphasized that all taxonomic categories are matters of scientific convenience based on abstractions from a continuous evolution. He recognizes that for little-known floras it is undesirable to analyse below the species level; but urged that in relatively well-studied floras the need is for intensive studies of infra-specific variation from every angle. His own researches have led him to the conclusion that taxonomic categories intergrade completely. He suggested that the term 'variety' should be used for every phenotype which is the expression of a different genotype, and that the term subspecies should be used only when a species is in process of breaking up into new ones. Names should be given to infra-specific groups only to serve some definite purpose, and in highly polymorphic species symbols might be used instead. Apomicts should receive distinct treatment.

Mr. A. J. Wilmott pointed out that confusion results from using the words species, subspecies and variety both for categories of variation in Nature and groups of different rank in the nomenclatural system. He suggested that the terms 'binome' and 'trinome' might be substituted for species and subspecies in the nomenclatural sense, leaving the latter free for application to categories of variation. True subspecies are parts of the present time section of a lineage which has become branched by isolation, but the branches of which are not yet completely separated. Varieties, on the other hand, are in a different category, being merely the observed phenotypic effects of separate genes, and not different *kinds* of organisms; they should not be given names under the same system as species and subspecies, but might be designated by symbols.

Mr. J. S. L. Gilmour dealt with the philosophical aspect of the subject and drew a distinction between taxonomic and non-taxonomic infra-specific categories. The former, which might be limited to subspecies, variety, and form, should be based so far as possible on the total attributes of the individuals concerned, while the latter should be based on a selection of attributes chosen for special purposes. Examples of such non-taxonomic categories are Dancer's 'commisceum', 'comparium', and 'convivium', based on interfertility data, and useful for investigating the relationship between such data and other attributes, such as morphological differentiation. He urged that this distinction is essential for the proper classification of infra-specific variability.

Mr. H. W. Parker showed that the practice of herpetologists is essentially similar to that of mammalogists. He believes, however, that owing to lack of other data, systematists have laid undue emphasis on geographical considerations, with invidious results. Recognition by trinomials of certain forms to the

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Disintegration of Heavy Nuclei

THROUGH the kindness of the authors I have been informed of the content of the letters[1] recently sent to the Editor of NATURE by Prof. Meitner and Dr. Frisch. In the first letter, these authors propose an interpretation of the remarkable findings of Hahn and Strassmann as indication for a new type of disintegration of heavy nuclei, consisting in a fission of the nucleus into two parts of approximately equal masses and charges with release of enormous energy. In the second letter, Dr. Frisch describes experiments in which these parts are directly detected by the very large ionization they produce. Due to the extreme importance of this discovery, I should be glad to add a few comments on the mechanism of the fission process from the point of view of the general ideas, developed in recent years, to account for the main features of the nuclear reactions hitherto observed.

According to these ideas, any nuclear reaction initiated by collisions or radiation involves as an intermediate stage the formation of a compound nucleus in which the excitation energy is distributed among the various degrees of freedom in a way resembling the thermal agitation of a solid or liquid body. The relative probabilities of the different possible courses of the reaction will therefore depend on the facility with which this energy is either released as radiation or converted into a form suited to produce the disintegration of the compound nucleus. In the case of ordinary reactions, in which the disintegration consists in the escape of a single particle, this conversion means the concentration of a large part of the energy on some particle at the surface of the nucleus, and resembles therefore the evaporation of a molecule from a liquid drop. In the case of disintegrations comparable to the division of such a drop into two droplets, it is evidently necessary, however, that the quasi-thermal distribution of energy be largely converted into some special mode of vibration of the compound nucleus involving a considerable deformation of the nuclear surface.

In both cases, the course of the disintegration may thus be said to result from a fluctuation in the statistical distribution of the energy between the various degrees of freedom of the system, the probability of occurrence of which is essentially determined by the amount of energy to be concentrated on the particular type of motion considered and by the 'temperature' corresponding to the nuclear excitation. Since the effective cross-sections for the fission phenomena for neutrons of different velocities seem to be of about the same order of magnitude as the cross-sections for ordinary nuclear reactions, we may therefore conclude that for the heaviest nuclei the deformation energy sufficient for the fission is of the same order of magnitude as the energy necessary for the escape of a single nuclear particle. For somewhat lighter nuclei, however, where only evaporation-like disintegrations have so far been observed, the former energy should be considerably larger than the binding energy of a particle.

These circumstances find their straightforward explanation in the fact, stressed by Meitner and Frisch, that the mutual repulsion between the electric charges in a nucleus will for highly charged nuclei counteract to a large extent the effect of the short-range forces between the nuclear particles in opposing a deformation of the nucleus. The nuclear problem concerned reminds us indeed in several ways of the question of the stability of a charged liquid drop, and in particular, any deformation of a nucleus, sufficiently large for its fission, may be treated approximately as a classical mechanical problem, since the corresponding amplitude must evidently be large compared with the quantum mechanical zero-point oscillations. Just this condition would in fact seem to provide an understanding of the remarkable stability of heavy nuclei in their normal state or in the states of low excitation, in spite of the large amount of energy which would be liberated by an imaginable division of such nuclei.

The continuation of the experiments on the new type of nuclear disintegrations, and above all the closer examination of the conditions for their occurrence, should certainly yield most valuable information as regards the mechanism of nuclear excitation.

N. BOHR.

At the Institute for Advanced Study,
Princeton, N.J. Jan. 20.

[1] [NATURE, 143, 239 and 275 (1939)].

Photoactivation of Solids and its Effect on Adsorption

CONSIDERABLE attention has been given recently to chemical processes involving an activating influence of a crystal excited by irradiation[1]. The mechanism of such photosensitized reactions, although unknown in detail, is generally believed to be a more or less complete transfer of the energy absorbed by the crystal to the reacting components, physically or chemically. Accordingly, the essential difference between photosensitized processes and real photochemical ones is the distance between the place of absorption and the place of reaction. But there must also be another, more general, effect of irradiation on the activity of crystals. Due to the change in the electronic state of the particles in the lattice by the absorption of light (change in charge and degree of polarization, formation of space charges, etc.), the forces between the particles are changed and, consequently, there is also a change in potential of the

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Instantaneous Emission of Fast Neutrons in the Interaction of Slow Neutrons with Uranium*

Recently it became known[1] that uranium can be split by neutrons into two elements of about equal atomic weight. In this fission of uranium the two elements produced have a large neutron excess; moreover they are probably produced in an excited nuclear state. One might therefore expect that these excited fragments instantaneously emit neutrons and that perhaps the number emitted is even larger than one per fission.

One might also expect a delayed emission of neutrons—as was first pointed out by Fermi—if some of the fragments go through one or more beta-transformations before they emit a neutron. Delayed emission of neutrons caused by the action of both slow and fast neutrons on uranium has recently been reported by Roberts, Meyer, and Wang,[2] who find a period of about 12 seconds.

In order to see if there is an instantaneous emission of neutrons from the fission of uranium we have performed the following experiment. We exposed uranium oxide to neutrons which were slowed down by paraffin wax, using as a source of neutrons a block of beryllium from which photoneutrons were liberated by the gamma-rays of radium. A helium-filled ionization chamber connected to a linear amplifier served as a detector for fast neutrons. The ionization pulses of the chamber were observed visually by means of a cathode-ray oscillograph and were recorded by the usual counting arrangement.

Figure 1 shows a diagram of the experimental arrangement. The ionization chamber is covered by a cadmium sheet cap G which prevents the thermal neutrons from penetrating to the helium ionization chamber. A cadmium sheet shield H, 0.5 mm thick, is used to cover the cylindrical box E which contains 2300 g of uranium oxide. The uranium oxide is screened from the thermal neutrons by this shield and can be exposed to them simply by removing the shield.

We observed about 50 pulses per minute from the helium chamber when we exposed the uranium oxide to the thermal neutrons in the absence of the cadmium shield H, but obtained only 5 pulses per minute when the uranium was screened from the thermal neutrons by the cadmium shield. The difference of about 45 pulses per minute we have to attribute to fast neutrons emitted from uranium under the action of thermal neutrons. It is reasonable to assume that this emission of fast neutrons is connected with the fission of uranium.

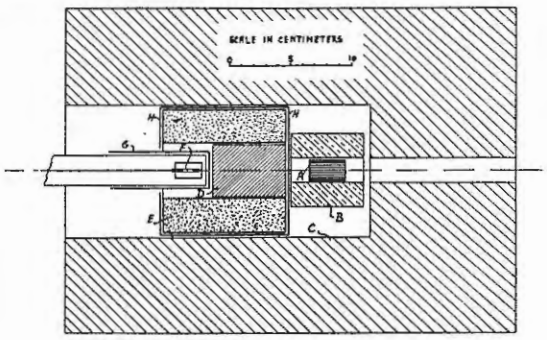

FIG. 1. Arrangement for the observation of the emission of fast neutrons from uranium. A, Radium. B, Beryllium block. C, Paraffin wax. D, Lead block. E, Box filled with uranium oxide. F, Ionization chamber. G, Cadmium sheet cap. H, Cadmium sheet shield.

Control experiments were carried out in which uranium was replaced by lead. The effect of the presence and absence of the cadmium shield H and the cadmium cap G was tested.

In order to estimate the number of fast neutrons emitted per fission under the action of thermal neutrons we used an ionization chamber lined with a thick layer of uranium oxide having an area of 25 cm². This uranium chamber was put in place of the helium chamber without otherwise materially changing the experimental arrangement. Under these conditions the uranium chamber gave about 45 fissions per minute. Assuming the range of the fission fragments to be about 0.005 g per cm² in uranium oxide, the observed 45 fissions per minute should occur in a surface layer, weighing 0.13 g, of the thick uranium oxide lining. Accordingly, about 800,000 fissions per minute should occur in the 2300 g of uranium oxide which was used in our experiment. By taking into account the solid angle, the size of the helium chamber and the pressure used, and by assuming that the "fission neutrons" have an average collision cross section in helium of 3.5×10^{-24} cm² we find the number of neutrons emitted per fission to be about two.

This number is of course only a rough estimate; the main cause of uncertainty is the considerable variation of the cross section of helium with the neutron energy in the region around one million volts.[3] A hydrogen-filled

ionization chamber is now being used in order to obtain a more accurate estimate. It seems to be established, however, that the order of magnitude is one neutron per fission.

Anderson, Fermi and Hanstein have independently, and by a different method, carried out experiments on the neutron emission connected with the fission of uranium. Our observations are consistent with their results, and we wish to thank them for communicating their results to us before publication.

While from our observations we can only say that the time delay involved in this "instantaneous" neutron emission appears to be less than one second, we should expect, for theoretical reasons, this emission to take place within less than 10^{-14} second.

We have also looked for a delayed emission of fast neutrons by performing the following experiment. The uranium oxide was irradiated for some length of time in the arrangement shown in Fig. 1. Then the radium was quickly removed from the beryllium block and the cathode-ray oscillograph screen was watched for a period of 15 seconds for an indication of a delayed emission of fast neutrons. After the radium is removed there is no gamma-ray background to set a lower limit for the observable helium recoil energy; the only slight background remaining is due to electrical fluctuations of the amplifier. In 50 experiments, corresponding to a total observation time of more than 12 minutes, we observed only two pulses which may or may not have been due to a delayed emission of fast neutrons. This is to be compared with the emission of 45 fast neutrons per minute, the number observed while the radium is inside the beryllium block. We conclude that, if slow neutrons falling on uranium cause a delayed emission of neutrons which are sufficiently fast for us to observe, their number must be very much smaller than the number of neutrons which we have observed in the instantaneous emission.

We are indebted to Dr. S. Seely for bis assistance in carrying out some of these experiments. We wish to thank the Department of Physics of Columbia University for the hospitality and the facilities extended to us, and also wish to thank the Association for Scientific Collaboration for enabling us to use one gram of radium in these experiments.

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WALTER H. ZINN

Pupin Physics Laboratories,
Columbia University,
New York, New York,
March 16, 1939.

* Publication assisted by the Ernest Kempton Adams Fund for Physical Research of Columbia University.

[1] O. Hahn and F. Strassmann, Naturwiss. 27, 11 (1939); L. Meituer and R. Frisch, Nature (February, 1939).
[2] R. B. Roberts, R. C. Meyer, and P. Wang, Phys. Rev. 55, 510 (1939).
[3] H. Staub and W. E. Stephens, Phys. Rev. 55, 131 (1939).

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Emission of Neutrons by Uranium*

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(Received August 14, 1939)

Fast neutrons emitted by uranium under the action of thermal neutrons were studied by using a radium-beryllium photoneutron source. The background due to the primary neutrons can be neglected since only a few of the photoneutrons are sufficiently fast to be counted. Data are obtained concerning the energy spectrum of the uranium fission neutrons by recording photographically by means of a linear amplifier and cathode-ray oscillograph the pulses due to helium atoms projected in an ionization chamber. Visual inspection of the record gives an upper limit of the spectrum of 3.5 Mev. The number of neutrons emitted is estimated by analyzing the pulse distribution of hydrogen atoms projected by uranium neutrons in an ionization chamber filled with hydrogen and argon. The number found is brought into relationship with the number of fissions, observed under comparable conditions, in an ionization chamber lined with a thin film of uranium oxide containing a known amount of uranium. In this way it is found that about 2.3 neutrons are emitted per fission. The method used would permit a greater accuracy in the determination of this number than the actual accuracy obtained in the present experiments. This number, together with the fission cross section and the cross section for radiative capture gives the number of neutrons produced for each thermal neutron absorbed in uranium.

WE reported[1] some time ago that fast neutrons are emitted—apparently instantaneously—from uranium under the action of thermal neutrons and we found, as a rough estimate, an average of two neutrons per fission process. This result was obtained by counting the helium recoil nuclei which the fission neutrons project in a helium-filled ionization chamber. The emission of neutrons in the fission of uranium was independently discovered by von Halban, Joliot and Kowarski[2] as well as by Anderson, Fermi and Hanstein,[3] who observed an increase of the thermal neutron density in water in the presence of uranium. Others[4] have investigated the same phenomenon.

Before this "instantaneous" emission had been observed, Roberts, Meyer and Wang[5] discovered a delayed emission of neutrons from uranium which apparently follows a beta-transformation of a half-life period of twelve seconds. We had found that the instantaneous emission was very much stronger than the delayed emission and we assumed that it corresponds to a direct ejection of neutrons from the uranium fragments, without being preceded by a beta-transformation, and that accordingly the time delay involved is far too small to be measured by the usual

* Publication assisted by the Ernest Kempton Adams Fund for Physical Research of Columbia University.

[1] L. Szilard and W. H. Zinn, Phys. Rev. **55**, 799 (1939).

[2] H. von Halban, F. Joliot and L. Kowarski, Nature **143**, 470 (1939).

[3] H. L. Anderson, E. Fermi and H. B. Hanstein, Phys. Rev. **55**, 797 (1939).

[4] G. P. Thomson, J. L. Michiels and G. Parry, Nature **143**, 760 (1939); G. von Droste and H. Reddeman, Nat. Wiss. **20/21**, 371 (1939).

[5] R. B. Roberts, R. C. Meyer and P. Wang, Phys. Rev. **55**, 510 (1939).

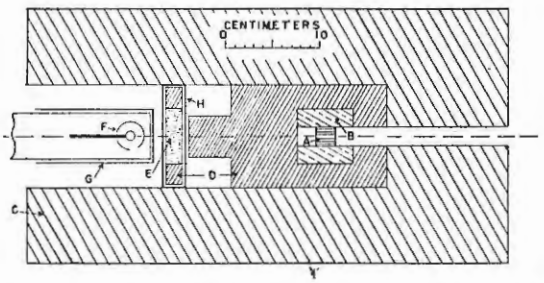


FIG. 1. Arrangement for the observation of the emission of fast neutrons from uranium. *A*—radium; *B*—beryllium block; *C*—paraffin wax; *D*—lead; *E*—uranium cell; *F*—spherical ionization chamber; *G*—cadmium sheet cap; *H*—cadmium sheet shield.

methods. This assumption was based on the arguments that it would be very difficult to explain the great abundance of the instantaneous neutron emission without assuming direct ejection and that no hard beta-rays were observed which should be expected to be present if the neutron emission followed a very short-lived beta-transformation. From direct experimental evidence, however, we could not exclude a delay smaller than one-tenth of a second. Gibbs and Thomson[6] have now shown by direct experiments that the delay is smaller than one-thousandth of a second and this appears to leave little doubt as to a direct ejection of neutrons.

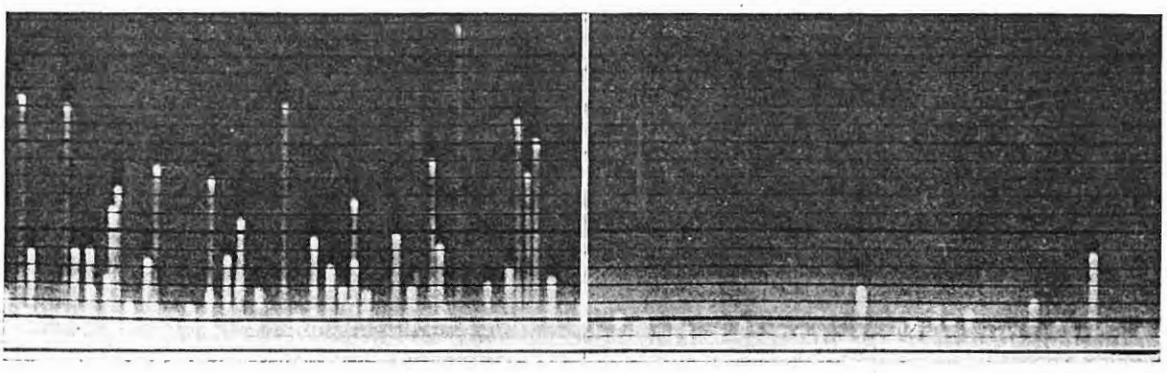
In the present experiments helium recoils were used for investigating the energy distribution of the fission neutrons, but hydrogen recoils were used for estimating the number emitted per fission.

The experimental arrangement is shown in Fig. 1. The source of thermal neutrons was about one gram of radium, *A*, placed in the center of a beryllium block, *B*, and surrounded by a paraffin cylinder, *C*. Fast neutrons emitted under the action of the thermal neutrons by about 430 grams of uranium metal enclosed in the cell *E*, were detected by the spherical ionization chamber, *F*. The pulses from the chamber were fed into a linear amplifier and were made visible by means of a cathode-ray oscillograph. A camera with a moving film was used to obtain a photographic record of the pulses appearing on the oscillograph screen.

Two such records are shown in Fig. 2; one was obtained in the absence and the other in the presence of the cadmium sheet shield, *H*. The shield *H* completely surrounds the uranium and shuts it off from most of the thermal neutrons, leaving a background of pulses which is partly due to particularly fast photoneutrons from the source, and partly due to fission neutrons from the uranium emitted under the action of the few thermal neutrons which pass through the cadmium shield. This background amounts to less than one pulse per minute.

The ionization chamber, which was filled with 10 atmospheres of hydrogen and 8 atmospheres of argon, contained a small amount of nitrogen. By removing the cadmium cap, *G*, from the chamber the nitrogen atoms in the chamber can be exposed to the action of thermal neutrons and

[6] D. F. Gibbs and G. P. Thomson, Nature **144**, 202 (1939).



(*a*) (*b*)

FIG. 2. (*a*) Oscillograph record of the fast neutrons from uranium. Cadmium sheet shield, *H* of Fig. 1, absent. Thermal neutrons falling on the uranium in the cell *E*. Ionization chamber filled with 10 atmospheres of hydrogen and 8 atmospheres of argon. (*b*) Record obtained with the cadmium shield *H* shutting off the thermal neutrons from the cell *E*.

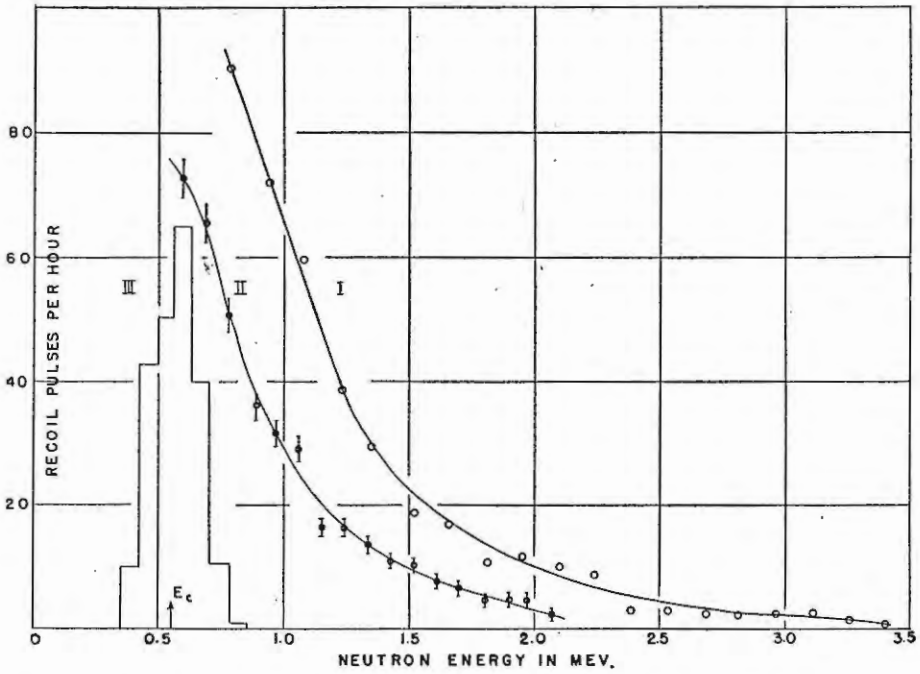


FIG. 3. Curve I: Pulse distribution due to helium recoils. Ionization chamber filled with 10 atmospheres of helium and 10 atmospheres of argon. Curve II: Pulse distribution $P(E)$ due to hydrogen recoils. Ionization chamber filled with 10 atmospheres of hydrogen and 8 atmospheres of argon. Curve III: Pulse distribution due to protons emitted, under the action of thermal neutrons, by a small amount of nitrogen in the chamber filled with 10 atmospheres of helium and 10 atmospheres of argon.

will then emit protons of about 0.6 Mev energy.[7] The pulses due to these protons were recorded and their distribution is shown in curve III of Fig. 3. This curve shows a sharp maximum which should correspond to an energy of about 0.6 Mev, and therefore this curve was used for calibrating the ionization chamber.

In order to find from the observed number of hydrogen recoils the number of neutrons which pass through the chamber it is necessary to know something about the energy distribution of the fission neutrons. This knowledge is required for two reasons. First, the scattering cross section of hydrogen is a function of the neutron energy; secondly, the observed pulse distribution of the hydrogen recoils is cut off at a certain energy E_c, which in this case was 0.55 Mev, in order to avoid the counting of pulses in the region which is affected by the gamma-ray background. Neutrons which have an energy below this cut-off energy, E_c, do not contribute to the recorded pulse distribution and their number has to be determined from the shape of the neutron spectrum, provided this spectrum is known.

If the time required for the collection of ions in the chamber were short compared with the time constant of the amplifier, the size of the pulses recorded by the oscillograph might be considered a fair measure of the energy which the recoil proton loses in the chamber. Even so, the size of the pulses cannot be considered a measure of the initial energy of the recoil protons if these lose only part of their energy in the chamber and are stopped by the walls. Therefore, if $R(E)dE$ is the number of recoil protons having an initial energy between E and $E+dE$, and if $P(E)dE$ is the number of recoil protons which lose in the chamber an amount of energy between E and $E+dE$, these two functions will be rather different in the high energy region where the range of the recoil protons cannot be neglected in comparison with the linear dimensions of the chamber. For the hydrogen-argon filled chamber

[7] J. Chadwick and M. Goldhaber, Proc. Camb. Phil. Soc. **31**, 612 (1935); T. W. Bonner and W. M. Brubaker, Phys. Rev. **49**, 778 (1936); M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 344 (1937).

which was used the two functions can be expected to coincide very nearly in the region of the cut-off energy E_c, and can be expected to differ widely for energies above 1.5 Mev.

For this reason helium recoils (which have about $\frac{1}{10}$ the range of recoil protons for equal neutron energies) had to be used instead of hydrogen recoils in order to find the upper end of the energy spectrum of the fission neutrons. Curve I, in Fig. 3, shows the pulse distribution of helium recoils obtained with 10 atmospheres of helium and 10 atmospheres of argon in the chamber. This curve shows that the spectrum of the fission neutrons extends to about 3.5 Mev. Though the existence of a small number of high energy neutrons such as reported by von Halban, Joliot and Kowarski,[8] is not inconsistent with our result, the number of neutrons having energies above 4 Mev appears to be too small to have much bearing on our estimate of the total number of fission neutrons.

Since the calibration of the chamber, which we performed by means of protons, is not entirely satisfactory for correlating the size of the pulses due to helium recoils witb the energy of the helium recoils, the helium-argon filled chamber was also calibrated by means of D+D neutrons of 2.5 Mev energy. The two calibrations coincided within the limits of the experimental error.

An estimate of the number of fission neutrons should be based on a count of hydrogen recoils rather than helium recoils since the scattering cross section of helium has a sharp maximum[9] for neutrons of about 1.0 Mev energy, and helium is therefore not suitable for the purposes of a quantitative estimate. It can be shown that, if the neutron-proton scattering is spherically symmetrical in the system of the center of gravity, the number of neutrons $N(E)dE$ which pass through the chamber, and which have an energy between E and $E+dE$, is given by:

$$N(E)=-\frac{E}{H\sigma(E)}\frac{dR(E)}{dE},$$

where $\sigma(E)$ is the scattering cross section of the proton and H is the number of hydrogen atoms in the ionization chamber. From this we derive, for the total number of neutrons, N, passing through the chamber:

$$N=\int_0^\infty N(E)dE=\frac{\alpha}{\sigma_{Av}H}\left[E_cR(E_c)+\int_{E_c}^\infty R(E)dE\right],$$

where α is the ratio of the total number of neutrons to the number of neutrons which have an energy in excess of E_c, and σ_{Av} is an average scattering cross section of the proton, the value of which has to be determined from the energy spectrum of the neutrons. Since we have:

$$\int_0^\infty R(E)dE=\int_0^\infty P(E)dE$$

and since, for the reasons stated above, we have with good approximation:

$$R(E)\backsimeq P(E) \quad \text{for} \quad E\leq E_c,$$

we can express N in terms of $P(E)$ instead of $R(E)$. We then have:

$$N=\frac{\alpha}{\sigma_{Av}H}\left[E_cP(E_c)+\int_{E_c}^\infty P(E)dE\right].$$

Let it now be assumed for the sake of argument that all the neutrons are emitted from a moving uranium fragment which has a mass number of about 120 and a kinetic energy of about 100 Mev. If all the neutrons were emitted from such a moving fragment with a single energy E_0, the energy distribution of the neutrons in the

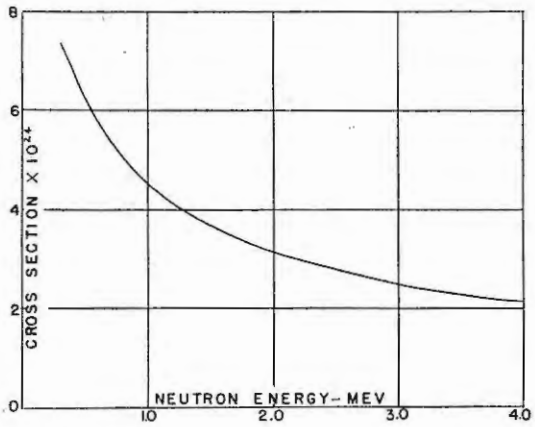


FIG. 4. Neutron-proton cross section as a function of neutron energy according to current theory.

[8] H. von Halban, F. Joliot and L. Kowarski, Nature **143**, 939 (1939).
[9] H. Staub and W. E. Stephens, Phys. Rev. **55**, 131 (1939).

laboratory reference system would stretch from:

$$E_{\min}=(0.9-E_0^{\frac{1}{2}})^2 \text{ Mev}$$

to:

$$E_{\max}=(0.9+E_0^{\frac{1}{2}})^2 \text{ Mev}.$$

It is easy to see that the neutrons should be uniformly distributed in this energy interval if their distribution is spherically symmetrical in the center of mass system. One obtains accordingly:

$$\alpha=(E_{\max}-E_{\min})/(E_{\max}-E_c)$$

and

$$\frac{1}{\sigma_{Av}}=\frac{1}{E_{\max}-E_c}\int_{E_c}^{E_{\max}}\frac{dE}{\sigma(E)}.$$

Using for $\sigma(E)$ the curve shown in Fig. 4 which has been theoretically derived,[10] the following values of α/σ_{Av} are obtained for various values of $E_{\max}$.

$E_{\max}$	2.0 Mev	3.0 Mev	4.0 Mev
α/σ_{Av}	$0.316\times10^{+24}$	$0.353\times10^{+24}$	$0.388\times10^{+24}$

The variation of α/σ_{Av} with $E_{\max}$ is so slight because of the manner in which both α and σ_{Av} decrease with rising $E_{\max}$.

The value of the expression:

$$E_cP(E_c)+\int_{E_c}^{\infty}P(E)dE$$

was found from the observed pulse distribution (curve II of Fig. 3) to be 13.7 pulses per minute. Since the number H of hydrogen atoms in the chamber was $H=6.9\times10^{+21}$ the number of neutrons passing through the chamber is

$$N=1.98\times10^{-21}(\alpha/\sigma_{Av}) \text{ per minute.}$$

If the cadmium cap G is removed the number of thermal neutrons reaching the uranium cell is increased and the number of fast neutrons passing through the ionization chamber is increased by the same factor. This factor was found to be 1.22 by filling the ionization chamber with pure hydrogen and then counting the hydrogen recoils giving rise to pulses above a certain arbitrarily set level, both in the presence and absence of the cadmium cap. Thus the number of neutrons N^* which pass through the chamber in the absence of the cadmium cap, G, is

$$N^*=2.415\times10^{-21}(\alpha/\sigma_{Av}) \text{ per minute.}$$

From N^* the number, K, of neutrons emitted per minute by the uranium was calculated by taking into account the geometrical factors, including the variation of the thermal neutron density within the uranium cell. K is thus found to be:

$$K=8.25\times10^{-19}(\alpha/\sigma_{Av}) \text{ per minute.}$$

In order to obtain the number of neutrons emitted per fission it is necessary to compare K with the number of fissions, L, which occur in the uranium under the conditions of this experiment. For this purpose both the ionization chamber and the uranium cell were removed and a parallel plate ionization chamber lined with a thick layer of uranium oxide was placed in the position previously occupied by the uranium cell. The number of fissions produced in this chamber was observed and found to be 19 per minute. The chamber was then calibrated by comparing the number of fissions obtained from the thick uranium oxide layer with the number of fissions obtained in the same chamber at the same thermal neutron intensity from a thin layer of uranium oxide containing 1.4 mg of uranium. The calibration was carried out by using a particularly strong neutron source, so as to obtain a sufficiently large number of counts from the thin layer. The ratio of the fission counts from the thick layer and from the thin layer was found to be 29.2, from which it is concluded that 196,000 fissions per minute should take place in the uranium cell containing 427.7 grams of uranium. This would be the number of fissions if the density of the thermal neutrons were not reduced in the uranium cell due to the absorption of such neutrons in uranium. We estimate that the average density of thermal neutrons within the cell is reduced by a factor of 0.715. The number of fissions L actually taking place within the cell is therefore

$$L=140{,}000 \text{ per minute.}$$

In order to estimate the reduction of the average thermal neutron density within the uranium cell leading to the factor of 0.715, we first explored the anisotropy of the thermal neutron radiation near the uranium cell by means

[10] J. Schwinger and E. Teller, Phys. Rev. 52, 286 (1937).

of a rhodium indicator, and then calculated the thermal neutron density within the uranium by assuming the distribution of thermal neutrons to be the same as would result from the superposition of two parallel thermal neutron beams, one directed away from the source and the other towards it, and having an intensity ratio of 3 to 1. We assume exponential absorption for these two beams within the uranium and an exponent corresponding to a half-value thickness in uranium of 14 g per cm^2.

The number of neutrons emitted per fission is

$$K/L=5.9\times10^{-24}(\alpha/\sigma_{Av}).$$

This number should be increased by perhaps 10 percent in order to correct for the fact that $P(E)$ does not exactly coincide with $R(E)$ even for $E\leq E_c$. The magnitude of this correction was estimated by comparing for D+D neutrons of 2.5 Mev energy the observed pulse distribution $P(E)$ with the calculated distribution $R(E)$ in the region of the low recoil energies. Making this correction one finds for ρ, the number of neutrons per fission

$$\rho=6.5\times10^{-24}(\alpha/\sigma_{Av}).$$

Using for α/σ_{Av} the value 0.353×10^{-24} which corresponds to $E_{max}=3$ Mev rather than to the actually observed upper limit of the fission neutron spectrum, one finds

$$\rho=2.3.$$

Since the fission neutrons hardly will be emitted with a single energy E_0, too high a value for α/σ_{Av} would be obtained if the observed value of the upper limit of the energy spectrum were used for E_{max}. In any case the error introduced by the uncertainty of the actual energy distribution of the fission neutrons should be small since one finds for

$$E_{max}=2 \text{ Mev} \quad \rho=2.0$$

and for

$$E_{max}=4 \text{ Mev} \quad \rho=2.5.$$

More serious, however, may be a number of experimental inaccuracies which might conceivably add up to give a considerable error.

The interest in the number of neutrons emitted per fission arose out of its obvious importance from the point of view of the possibility of nuclear chain reactions. At present we have the following set of values: number of neutrons per fission, 2.3; fission cross section,[11] 2.0×10^{-24} cm^2; cross section for radiative capture[12] 1.3 or 1.2×10^{-24} cm^2. According to these values, the number of neutrons emitted by uranium per thermal neutron absorbed should be 1.4, which agrees with the value of 1.5 recently obtained by another method by Anderson, Fermi and Szilard.[13] Too much significance should not be attributed to this agreement, since the values given above are subject to fairly wide experimental errors.

If required the present experiments could be repeated with greater accuracy since the method used is quite capable of being applied with greater precision. Moreover, it gives the number of neutrons per fission independently of the value of the fission cross section which enters into the method used by von Halban, Joliot and Kowarski. These authors report[14] a value of 3.5 ± 0.7 neutrons per fission.

It should be mentioned that it appears to be essential for the method presented here to work with a low background count. The background is due to the primary neutrons and can be kept small by using a photoneutron source. We did not find it possible to obtain quantitative results by using neutrons from radon-beryllium sources or from the D+D reaction on account of the high background count due to the primary neutrons.

We are indebted to Dr. G. N. Glasoe for suggesting the method of obtaining the photographic records and for much valuable advice in this connection, and to Dr. E. T. Booth for determining by means of an alpha-particle count the uranium content of the thin uranium sheet which we used for purposes of calibration. Also, we wish to thank the Department of Physics of Columbia University for the laboratory facilities placed at our disposal and the Association for Scientific Collaboration for enabling us to obtain the radium used in this experiment.

[11] H. Anderson, E. Booth, J. Dunning, E. Fermi, G. Glasoe and F. Slack, Phys. Rev. **55**, 511 (1939).
[12] H. v. Halban, L. Kowarski and P. Savitch, Comptes rendus **208**, 1396 (1939); H. L. Anderson and E. Fermi, Phys. Rev. **55**, 1106 (1939).
[13] H. L. Anderson, E. Fermi and L. Szilard, Phys. Rev. **56**, 284 (1939).
[14] H. von Halban, F. Joliot and L. Kowarski, Nature **143**, 680 (1939).

Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium,by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work, which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

Yours very truly,

A. Einstein

(Albert Einstein)

Fission of Uranium under Deuteron Bombardment

SINCE the phenomenon of neutron-induced fission of the uranium and thorium nuclei is now indisputably established, attention may be turned to the possible efficacy of other bombarding particles in this respect. An outline is here presented of evidence suggesting that high-energy deuterons are, in fact, capable of producing fission in uranium.

The following experimental arrangement has been used. One inside surface of a copper box is covered with a 20 mgm./cm.^{2} layer of uranium metal, and is bombarded by deuterons passing through an aperture in the opposite side of the box. An inside pocket on one of the other walls contains metal foils for the purpose of collecting particles projected from the target through an aperture in the pocket. A thickness of 2 mm. S.P. aluminium is always present to protect the collecting foil from the low-energy products due to mechanical disintegration of the target. Bombardments of about 1 μamp. for ten minutes are convenient, and are found to produce on the collector activities of intensity suitable for measuring with a Geiger counter.

It is necessary to estimate what part of the activity on the collector is due to general neutron radiation and to deuterons scattered from the target. In the pocket are placed three foils of 3·3 mgm./cm.^{2} aluminium, F, D and N in order of proximity to the target, and a single thickness of half-millimetre copper sheet between the foils D and N. Five minutes after a 4 μamp./min. bombardment with 9 Mv. deuterons, it is found that the neutron effect of the irradiation has produced in N a small activity of 40 counts per minute; the neutron effect is eliminated from D and F simply by subtraction of this N effect. D's activity measures the scattered-deuteron effect and is initially about 100 counts per minute, decaying with a half-life of 2·3 min. to reach a negligibly small value after 20 min. F's activity, however, is about 1,500 counts per min., and is much longer-lived, although with a target entirely of lead, F as well as D shows only a D effect.

The decay curve for F's activity has been followed for about 7 hours and has been compared with that calculated from Frisch's formula[1] for the decay of multiplex activity. The measure of agreement is so substantial as to preclude the possibility of a merely accidental coincidence.

A stack of six 0·66 mgm./cm.^{2} aluminium foils has been placed in the pocket and after the lapse of 30 minutes (when the D effect has decayed) the activities are found to decrease regularly through the stack, reaching inappreciably small values in the fifth and sixth foils. Regarding another aspect, the fact that replacement of aluminium as the collector material by silver causes no significant difference in the decay curve, suggests that the activity has been implanted rather than induced. The evidence thus indicates that radioactive nuclei are projected from the uranium target with a range of the order of 2 cm.; this occurrence is evidently to be ascribed to a fission of the uranium nucleus.

It is important to assess the magnitude of the fission effect caused by background neutron radiation, and for this purpose there has been enclosed in the pocket itself a layer of uranium, separated from F by 2 mm. S.P. of aluminium, and from the target by the copper sheet, this arrangement necessarily reproducing fairly closely that activity in F which is due to neutron-induced fission. The intensity in this case is less than one twentieth of that observed in the positive experiment.

Approximate measurements have been made on the excitation function for deuteron-induced fission, using aluminium absorbers to modify the energy of the beam and a suitable disposition of diaphragms to protect the collector against deuterons scattered from the absorbers. The threshold for the process appears to lie at about 8 Mv., and the cross-section increases rapidly in the range 8–9 Mv.

The conclusions drawn from these preliminary experiments would receive unequivocal confirmation from a chemical identification of the fragment nuclei or a detection of their large ionization impulses in an ionization chamber. It might also prove profitable to examine the effects given by others of the heaviest elements (especially thorium).

Dr. R. S. Krishnan and other colleagues of the Cavendish cyclotron group have rendered me indispensable assistance, and I am indebted also to Prof. J. D. Cockcroft for pertinent suggestions.

Cavendish Laboratory, Cambridge. Aug. 26. D. H. T. GANT.

[1] NATURE, 143, 852 (1939).

Absorption of Polymolecular Films in the Infra-Red

THE use of infra-red absorption spectra as a means of investigating molecular structure has still to be extended to surface films. Until very recently, the possibilities of this extension seemed remote, since a monomolecular layer does not contain enough molecules per square centimetre to produce measurable absorption. Thus it is found experimentally that approximately 10^{19} molecules are required to produce appreciable absorption in a beam of 1 sq. cm. cross-section, whereas the number of molecules per square centimetre in a monomolecular layer is about 5×10^{14}. With the production of polymolecular films close to 1,000 molecules thick, the possibility of detecting absorption still seemed slight, but technically feasible, if a method employing several reflections through such a film were employed.

As a matter of interest, it was decided to try whether any absorption could be detected using a single reflection through a film of methyl stearate 700 molecules thick, deposited on a chromium-plated strip of metal. We were surprised to find that the well-known absorption at 3·3 μ due to CH groups was easily detectable, showing about 30 per cent absorption, while other weaker bands were noticeable between 6 μ and 10 μ. Next, a film only 200 molecules thick was tried. This still gave the 3·3 μ band with appreciable intensity. These results mean that absorption spectra were being obtained from approximately 10^{17} molecules, instead of the customary 10^{19}. In other words, the absorption coefficient of a molecule in the infra-red seems to be considerably increased when it is in a surface film.

The possible causes of this will not be discussed here. The purpose of this note is merely to record this fact, which opens up a new and potentially interesting field of research in infra-red spectroscopy and its application to problems of molecular structure. In particular, this may prove to be a very suitable method of studying protein molecules.

We wish to express our thanks to Dr. Stenhagen, who prepared the films.

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Letters to the Editor

The Editor does not hold himself responsible for opinions expressed by his correspondents. He cannot undertake to return, or to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.*

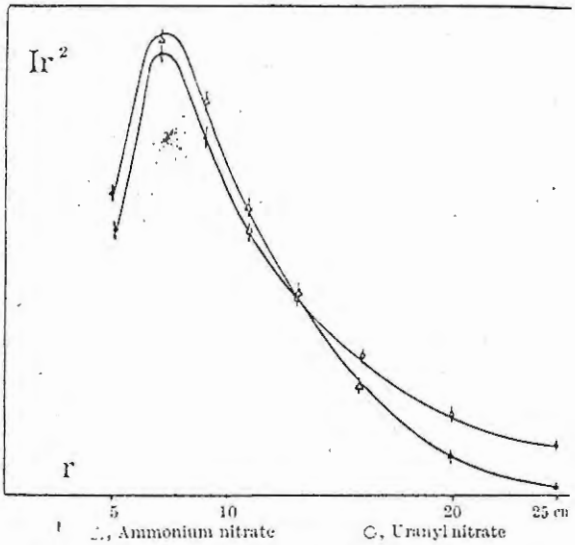
NOTES ON POINTS IN SOME OF THIS WEEK'S LETTERS APPEAR ON P. 478.

CORRESPONDENTS ARE INVITED TO ATTACH SIMILAR SUMMARIES TO THEIR COMMUNICATIONS.

Liberation of Neutrons in the Nuclear Explosion of Uranium

RECENT experiments[1,2] have revealed the existence of a new kind of nuclear reaction: neutron bombardment of uranium and thorium leads to an explosion of the nucleus, which splits up into particles of inferior charge and weight, a considerable amount of energy being liberated in this process. Assuming a partition into two particles only, so that the nuclear mass and charge of uranium have to be distributed between two lighter nuclei, the latter contain considerably more neutrons than the heaviest stable isotopes with the same nuclear charges. (A splitting into, for example, ^{98}Rb and ^{141}Cs means an excess of 11 neutrons in the first, and of 8 neutrons in the second of these two nuclei.) There seem to be two possibilities of getting rid of this neutron excess. By the emission of a β-ray, a neutron is transformed into a proton, thus reducing the neutron excess by two units; in the example given above, five and four successive β-activities respectively would be needed to restore the neutron-proton stability ratio. In fact, the explosion products have been observed to be β-active and several periods have been recorded, so that a part, at least, of the neutron excess is certainly disposed of in this way. Another possible process is the direct liberation of neutrons, taking place either as a part of the explosion itself, or as an 'evaporation' from the resulting nuclei which would be formed in an excited state.

In order to find some evidence of this second phenomenon, we studied the density distribution of the thermal neutrons produced by the slowing down of photo-neutrons from a Ra γ - Be source in a 1·6 molar solution of uranyl nitrate and in a 1·6 molar solution of ammonium nitrate (the hydrogen contents of these two solutions differ by only 2 per cent). Plotting Ir^2 as a function of r (where r is the distance between the source and a given point, and I is the local density of thermal neutrons at the same point, measured by the activity induced in a dysprosium detector), a curve is obtained the area of which is proportional to $Q.\tau$, Q being the number of neutrons per second emitted by the source or formed in the solution and τ the mean time a neutron spends in the solution before being captured[3,4]. Any additional nuclei, which do not produce neutrons, brought into the solution, will increase the chances of capture and therefore decrease τ and the area. If, however, these dissolved nuclei are neutron-producing, Q will be greater and the area of the curve will tend to increase. Evidence of neutron production, as indicated by an actual increase of the area, will only be obtained if the gain through Q (neutron production) is greater than the loss through τ (neutron capture). This loss can anyway be studied separately, since it has been shown[5] that the introduction of nuclei which act merely by capture or by increasing the hydrogen content of the solution can affect the shape of th density curve only in a characteristic way: the modi fied curve can always be brought to coincide wit the primitive curve by multiplying all abscissæ b a suitable factor and all ordinates by another facto



The accompanying graph shows the two curve obtained. At small distances from the source th neutron density is greater in the ammonium solutio than in the uranyl solution; at distances greate than 13 cm., the reverse is true. In other words the decrease of the neutron density with the distanc is appreciably slower in the uranyl solution.

The observed difference must be ascribed to th presence of uranium. Since the two curves cannot be brought to coincide by the transformation mentioned above, the uranium nuclei do not act by capture only; an *elastic* diffusion by uranium nuclei would have an opposite effect: it would 'contract' the abscissæ, instead of stretching them. The density excess, shown by the uranyl curve beyond 13 cm. must therefore be considered as a proof of neutron production due to an interaction between the primary neutrons and the uranium nuclei. A reaction of the well-known $(n,2n)$ type is excluded because our primary neutrons are too slow for such a reaction (90 per cent of Ra + Be photo-neutrons have energies smaller than 0·5 Mev. and the remaining 10 per cent are slower than 1 Mev.).

The degree of precision of the experiment does not permit us to attribute any significance to the small increase of the area in the uranyl curve (as compared to the ammonium curve), which we obtain by extrapolating the curves towards greater distances. In any event, an inferior limit for the cross-section for the production of a neutron can be obtained by

ssuming that the density excess due to this production is equal throughout the whole curve to the xcess observed at $r = 25$ cm.; this limit, certainly nferior to the actual value, is 6×10^{-25} cm.^{2}.

Our measurements yield no information on the nergy of the neutrons produced. If, among these eutrons, some possess an energy superior to 2 Mev., ne might hope to detect them by a (n,p) process, or example, by the $^{32}S(n,p)^{32}P$ reaction. An experiment of this kind, Ra γ - Be still being used as the rimary neutron source, is under way.

The interest of the phenomenon observed as a step owards the production of exo-energetic transmutaion chains is evident. However, in order to establish uch a chain, more than one neutron must be produced for each neutron absorbed. This seems to be the ase, since the cross-section for the liberation of a eutron seems to be greater than the cross-section for he production of an explosion. Experiments with olutions of varying concentration will give informaion on this question.

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Joliot, F., *C.R.*, 208, 341 (1939).
Frisch, O. R., NATURE, 143, 276 (1939).
Amaldi, E., and Fermi, E., *Phys. Rev.*, 50, 899 (1936).
Amaldi, E., Hafstad, L., and Tuve, M., *Phys. Rev.*, 51, 896 (1937).
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Products of the Fission of the Uranium Nucleus

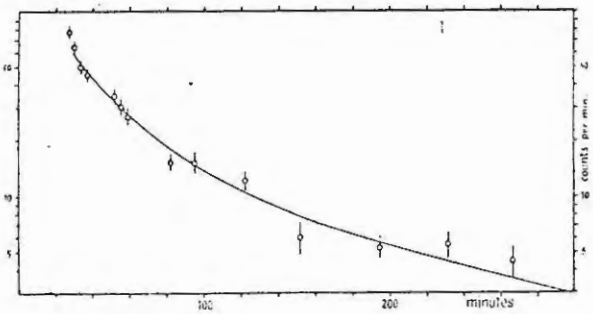
O. Hahn and F. Strassmann[1] have discovered a new type of nuclear reaction, the splitting into two smaller nuclei of the nuclei of uranium and thorium under neutron bombardment. Thus they demonstrated the production of nuclei of barium, lanthanum, strontium, yttrium, and, more recently, of xenon and cæsium.

It can be shown by simple considerations that this type of nuclear reaction may be described in an essentially classical way like the fission of a liquid drop, and that the fission products must fly apart with kinetic energies of the order of hundred million electron-volts each[2]. Evidence for these high energies was first given by O. R. Frisch[3] and almost simultaneously by a number of other investigators[4].

The possibility of making use of these high energies in order to collect the fission products in the same way as one collects the active deposit from alpha-recoil has been pointed out by L. Meitner (see ref. 3). In the meantime, F. Joliot has independently made experiments of this type[5]. We have now carried out some experiments, using the recently completed high-tension equipment of the Institute of Theoretical Physics, Copenhagen.

A thin layer of uranium hydroxide, placed at a distance of 1 mm. from a collecting surface, was exposed to neutron bombardment. The neutrons were produced by bombarding lithium or beryllium targets with deuterons of energies up to 800 kilovolts. In the first experiments, a piece of paper was used as a collecting surface (after making sure that the paper did not get active by itself under neutron bombardment). About two minutes after interrupting the irradiation, the paper was placed near a Geiger-Müller counter with aluminium walls of 0·1 mm. thickness. We found a well-measurable activity which decayed first quickly (about two minutes half-value period) and then more slowly. No attempt was made to analyse the slow decay in view of the large number of periods to be expected.

The considerable intensity, however, of the collected activity encouraged us to try to get further information by chemical separations. The simplest experiment was to apply the chemical methods which have been developed in order to separate the 'transuranium' elements from uranium and elements immediately below it[6]. The methods had to be slightly modified on account of the absence of uranium in our samples and in view of the light element activities discovered by Hahn and Strassmann[1].



In these experiments, the collecting surface was water, contained in a shallow trough of paraffin wax. After irradiation (of about one hour) a small sample of the water was evaporated on a piece of aluminium foil; its activity was found to decay to zero. It was checked in other ways, too, that the water was not contaminated by uranium. To the rest of the water we added 150 mgm. barium chloride, 15 mgm. lanthanum nitrate, 15 mgm. platinum chloride and enough hydrochloric acid to get an acid concentration of 7 per cent. Then the platinum was precipitated with hydrogen sulphide, in the usual way; the precipitate was carefully rinsed and dried and then placed near our counter.

The results of three such experiments were found to be in mutual agreement. The decay of the activity was in one case followed for 28 hours. For comparison, a sample of uranium irradiated for one hour was treated chemically in the same way. The two decay curves were in perfect agreement with one another and with an old curve obtained by Hahn, Meitner and Strassmann under the same conditions. In the accompanying diagram the circles represent our recoil experiment while the full line represents the uranium precipitate. A comparison of the activity (within the first hour after irradiation) of the precipitate and of the evaporated sample showed that the precipitate contained about two thirds of the total activity collected in the water. After about two hours, however, the evaporated sample was found to decay considerably more slowly than the precipitate, presumably on account of the more long-lived fission products found by Hahn and Strassmann[1].

From these results, it can be concluded that the 'transuranium' nuclei originate by fission of the uranium nucleus. Mere capture of a neutron would give so little kinetic energy to the nucleus that only a vanishing fraction of these nuclei could reach the water surface. So it appears that the 'transuranium'

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LETTERS TO THE EDITOR

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NOTES ON POINTS IN SOME OF THIS WEEK'S LETTERS APPEAR AT P. 811.

NUCLEAR PHYSICS

Control of the Chain Reaction involved in Fission of the Uranium Nucleus

IT has recently been shown that the number[1] of neutrons liberated[2] in the nuclear fission of a uranium nucleus is sufficiently high to make the realization of a self-perpetuating reaction chain seem possible. The danger that a system containing uranium in high concentration might explode, once the chain is started, is considerable. It is therefore useful to point out a mechanism which gives the possibility of controlling the development of such a chain.

We form an expression which is characteristic for the behaviour of the chain:

$$\nu'' = \frac{A_f}{A}\nu(1-\alpha), \quad . \quad . \quad (1)$$

A_f being the product of the cross-section for nuclear fission for a thermal neutron of the uranium nucleus with the concentration of the uranium; A_i the product of the absorption cross-section for thermal neutrons of the nucleus of kind i multiplied with its concentration; A the sum of all A_i's, which is to be taken over all kinds of nuclei present in the solution; ν is the average number of neutrons liberated in one fission, α the average probability for a neutron to diffuse out of the system before being absorbed.

The energy liberated by the chain will be

$$E = NF, \quad . \quad . \quad (2)$$

F being the energy liberated in one fission and N the number of fissions produced by the chain. We have

$$N = \nu'' + \nu''^2 + \nu''^3 + \ldots\ldots \quad (3)$$

The chain gives thus a quantity of energy, which is increasing rapidly with time, if ν'' is greater than 1. Let us consider the case of a chain which is due to fission produced by thermal neutrons; that is, a chain propagating itself in a system containing sufficient hydrogen for the slowing down of the neutrons.

If the cross-sections for capture or fission of all nuclei present follow the $1/v$ law, ν'' will not depend on the velocity of the neutrons and therefore not on the temperature of the system (since α will in practice be small and since it depends in the first place on the distance necessary for slowing down the neutron; the temperature has, of course, an effect, although it will be very small).

Let us, however, introduce an absorbent, such as cadmium, the cross-section of which does not depend on the neutron energy in the thermal region. We will have, instead of (1),

$$\nu'' = \nu\frac{A_f}{A' + A_c}(1-\alpha), \quad . \quad . \quad . \quad (4)$$

where A' is the sum of all A_i's following the $1/v$ law and A_c is a constant, the term due to the newly added absorbent. ν'' will now decrease with increasing temperature. At a temperature, which will be characteristic for the composition and the geometrical constants of the system, ν'' will become smaller than unity and the system will stabilize itself somewhere near this temperature; the equilibrium being determined by the fact that the amount of energy given out per unit of time by the system (in the form of heat and nuclear radiation) is equal to the energy produced by the system. Similar questions have been discussed by F. Perrin[3].

Added in proof: In the case of a chain propagating itself by thermal neutrons, the time necessary for the slowing down and for the absorption of a neutron, that is, its mean life, is of the order of 10^{-4} sec. If one makes ν'' as small as 1007, it needs 100 times the mean life of a neutron or about 10^{-2} sec. to double the number of neutrons, and with that the energy liberated per unit of time. It is therefore possible to control the development of the chain by a periodical interaction of absorbers which break up the chains by entering the system.

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[1] von Halban, jun., H., Joliot, F., and Kowarski, L., NATURE, 143, 470 (1939).

[2] von Halban, jun., H., Joliot, F., and Kowarski, L., NATURE, 143, 680 (1939). Roberts, R., Meyer, R., and Wang, P., *Phys. Rev.*, 55, 510 (1939). Haenny, C., and Rosenberg, A., *C.R.*, 208, 898 (1939). Szilard and Zinn (private communication). Huber and Buddinger (private communication).

[3] Perrin, F., *C.R.*, in the Press.

A series of experiments with varying number of α-rays per c.c. gave the following figures.

Time of irradiation in days	α	r from equation (2)	c/c_0	
			Experimental determination	Theoretical values from equation (1)
0·8	$0·9 \times 10^{13}$	0·07	0·91	0·93
2·0	1·9 ,,	0·14	0·85	0·87
4·1	3·3 ,,	0·26	0·82	0·77
11·8	5·6 ,,	0·43	0·72	0·65

In view of the approximations made and the experimental difficulties involved, the agreement between the experimentally determined and the calculated relative concentrations of unchanged molecules is quite satisfactory and supports the assumption that every haemocyanin molecule hit by an α-particle is split. This means that, out of the energy received in any part of the molecule, a portion large enough to cause splitting is transferred to the bond holding the two halves together.

As yet we have not carried out measurements of the absolute number of ultra-violet light quanta active in this splitting, but the independence of temperature points to a quantum yield of unity. It is of interest to note that from studies of the action of various rays on the mutation rate, it has been inferred that the production of a single ion pair within a sensitive spot of the cell, probably the gene, produces mutation[3]. There seems to be a certain analogy between this finding and our results.

The different behaviour of haemocyanin on one hand and haemoglobin and serum albumin on the other seems to us to be of considerable importance. It shows that the former molecule is easily dissociated by absorption of energy while the latter ones are very stable against a raising of the energy-levels so long as secondary chemical reactions are excluded.

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[1] Svedberg, T., and Brohult, S., NATURE, 142, 830 (1938).
[2] Sanigar, E. B., Krejci, L. E., and Kraemer, E. O., *Biochem. J.* 33, 1 (1939).
[3] Cf. Stubbe, H., "Genmutation", 327 (Berlin, 1938).

Energy of Neutrons liberated in the Nuclear Fission of Uranium induced by Thermal Neutrons

IT has been shown that *fast* neutrons are liberated in the process of nuclear fission induced in uranium by primary *thermal* neutrons. Two different methods of detection have been used: in the first method[1], the primary and (if any) secondary neutrons are absorbed in a medium in which an endo-energetic reaction can take place, leading to the formation of an easily detectable radioactive nucleus. If the energy threshold is situated above the maximum energy of the primary neutrons, any positive results observed must be ascribed to the secondary neutrons. In the second method[2], elastic collisions of fast neutrons with heavier nuclei are observed by means of an ionization chamber filled with a gas at atmospheric pressure and connected to a linear amplifier. In order to study separately the effect due to the primary thermal neutrons, the experiment is performed with, and without, a cadmium shield between the source and the uranium mass.

The first method having shown us that fast secondary neutrons are produced with energies of at least 2 Mev. (sufficient to transform ^{32}S into radioactive ^{32}P in detectable quantities), we sought to ascertain, by the second method, whether neutrons of energy notably higher than 2 Mev. are also present in the secondary radiation. In our experiment, the oxygen-filled ionization chamber was placed in a nearly cubical box (9 cm. × 9 cm. × 8 cm.) containing uranium oxide and surrounded by a thick layer of paraffin wax. The source (300 mgm. Raγ + Be), surrounded by a lead shield (5 cm. in the direction of the chamber) was buried in the wax. In order to absorb thermal neutrons, the uranium box could be screened on all sides with a cadmium foil. The pulses were recorded either in the presence or in the absence of this foil and the part of the effect (projection of oxygen nuclei by fast neutrons liberated in the uranium) due to thermal neutrons could thus be evaluated.

In view of the large number of of accidental pulses due to the strong γ-radiation emitted by the source, only nuclei recoiling with at least 1·5 Mev. could be taken into consideration. The distribution curve shows that the frequency of pulses observed falls off rapidly between 1·5 Mev. and 2·5 Mev.; between 2·5 Mev. and 3·7 Mev. the frequency decreases much more slowly, pulses observed in this second region being, however, very rare. The total number of pulses recorded is small (with cadmium: 84 pulses in 90 minutes; without cadmium: 161 pulses in 90 minutes); but it appears clearly that recoils with energy of about 2·5 Mev. are notably more frequent in the absence of cadmium and, therefore, that *neutrons possessing an energy of at least* 11 Mev. *are liberated in uranium irradiated with thermal neutrons.*

The high energy of these fast neutrons shows that their parent nuclei are in a highly excited state at the moment of their liberation, which is probably simultaneous with the fission. In this way a non-negligible fraction of the fission energy is disposed of; a further fraction is carried off by the β- and γ-rays afterwards emitted by the nuclei produced in the fission. The remainder available as kinetic energy for these recoiling nuclei is therefore considerably smaller than the total amount of energy liberated in the fission process (about 200 Mev.).

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[1] Dodé, M., von Halban, jun., H., Joliot, F., and Kowarski, L., *C.R.*, 208, 995 (1939).
[2] Szilard, L., and Zinn, W., *Phys. Rev.*, 55, 799 (1939).

Homometric Structures

IN connexion with a recent discussion[1] of the question of the uniqueness of an X-ray crystal analysis, Prof. Linus Pauling has directed my attention to a curious property of the point position[2] $Th^7 - Ia3 - 24(d)$. Pauling and Shappell[3] have shown that this point position, which involves a single parameter u, has a structure factor which is even in u, while parameter values $+u$ and $-u$ correspond to the structures which are not identical

temperatures below the critical range, and the structures produced in steels of different carbon content cooled at different rates or allowed to transform at different constant sub-critical temperatures.

Since the investigations of Dejean in 1917 and Portevin in 1919, it has been known that a progressive increase in the rate of cooling results in the first place in a gradual lowering of the normal changes, and in the second place, when a certain critical rate is exceeded, in the discontinuous depression of the changes to a lower temperature at which martensite is formed. Researches carried out since 1930 in the Kaiser Wilhelm Institute have contributed to present knowledge about the various changes and the relations between them. It has been shown, for example, that once the rate of cooling is sufficiently rapid to prevent any changes taking place above the martensite point, further increase in the rate of cooling does not produce further lowering of the martensite change. Thus a line may be drawn in the iron-carbon diagram to indicate the temperature at which the martensite change begins in steels of different carbon content, or a three-dimensional diagram may be drawn to show the relations between carbon content, rate of cooling and the temperatures of the transformations. It has also been known for some time that when steel is cooled to about 500° C. at a rate that suppresses the normal change, and is then cooled more slowly or maintained at constant temperature, an intermediate transformation occurs. The investigations with which Prof. Wever has been associated indicate, however, that this intermediate transformation may also proceed to some extent during continuous cooling at certain rates. Thus by cooling steels at progressively increasing rates, three kinds of changes may be obtained, namely, the normal, the intermediate and the martensitic.

By means of a magnetic balance, the progress of the normal and the intermediate changes at different constant temperatures has been studied. This work has shown that the rate of the normal austenite-pearlite transformation increases to a maximum as the temperature at which it is caused to take place is lowered, but further lowering leads to a diminution in the rate and it finally becomes extremely slow. A characteristic of this change is that at all temperatures there is a period of delay before it begins. At temperatures below that at which the normal change can take place the intermediate change occurs. This begins immediately, proceeds at a rate that becomes more rapid as the temperature is lowered, and continues to an extent that increases as the temperature is lowered. At still lower temperatures the martensite change takes place with great rapidity, and investigations on iron-carbon-nickel and iron-carbon-manganese alloys have shown that the martensite change in carbon steels corresponds to the $\gamma \rightarrow \alpha$ change in iron-nickel or iron-manganese alloys.

FISSION OF URANIUM NUCLEI

PROF. OTTO HAHN of the Kaiser Wilhelm Institut für Chemie, Berlin-Dahlem, was guest lecturer, on the invitation of the Royal Society, at the Royal Institution on Friday, June 23. Prof. Hahn's subject was "The Fission of Uranium Nuclei by Neutrons", and his account was chiefly historical. As the first definitely to establish the production of elements of medium atomic weight (fission products) when uranium is bombarded by neutrons, Prof. Hahn naturally confined himself mainly to describing the chemical method of investigation used by his colleagues and himself.

He described in detail how, in the process of confirming and extending the earlier investigations of Fermi and Curie and Savitch, Dr. Strassmann and he were forced to conclude that short-lived isotopes of barium and lanthanum were produced from uranium. These bodies could be separated from radium and actinium isotopes, but not at all from inactive barium or lanthanum, respectively, either by fractionation or by chemical means. Meitner and Frisch discussed these results in terms of division of the heavy nucleus into roughly equal fragments and Frisch showed, for the first time by a physical experiment, that the predicted large amount of energy is released in the act of fission. Thereafter, said Prof. Hahn, the whole subject was widely studied in a great many laboratories throughout the world. In his own laboratory, the chemical investigation was continued and the production of xenon, as fission product together with strontium, was established. The active barium and lanthanum, on this showing, arise chiefly as decay products following xenon and cæsium isotopes.

Up to this point, Prof. Hahn had described only previously unknown activities, but he went on to show how first one and then another of the so-called trans-uranic elements, postulated to explain most of the early work on the uranium disintegration, were proved, by purely chemical means, also to belong to the middle, rather than the end, of the periodic table. This was established by physical methods in other laboratories; but his own experiments had carried the matter further in one particular respect. After a great deal of labour, he had been able to show that the eka-iridium of the earlier classification contained molybdenum as well as tellurium—even though the half-value periods of the two active isotopes were distressingly similar! There remained only the task of applying the same methods of exact chemistry to the other activities which had not so far been studied, Prof. Hahn said, for his own contribution to the problem to be complete.

In the discussion which followed this most interesting lecture, Prof. Niels Bohr gave an account of the theoretical treatment of the fission problem recently undertaken by Dr. J. A. Wheeler and himself in the United States, and further contributions were made by Prof. M. L. E. Oliphant, Dr. E. Bretscher, Prof. G. P. Thomson and others.

Dr. Bretscher mentioned the results of preliminary experiments using large quantities of lead tetra-ethyl, which appear to show that fission occurs (though with a very small cross-section) with lead under fast neutron bombardment.

N. F.

Number of Neutrons Liberated in the Nuclear Fission of Uranium

RECENT experiments have shown that neutrons are liberated in the nuclear fission of uranium induced by slow neutron bombardment: secondary neutrons have been observed which show spatial[1], energetic[2] or temporal[3] properties different from those which primary neutrons possess or may acquire. Such observations give no information on the mean number of neutrons produced per nucleus split; this number ν may be very small (less than 1) and the result of the experiment will still be positive.

We are now able to give information on the value of ν. Let us consider the curve representing the density distribution of neutrons slowed down in an aqueous solution surrounding a primary neutron source[1]; the area S of this curve is proportional to $Q.\tau$, Q being the number of neutrons per second emitted by the source or formed in the solution, and τ the mean time a neutron spends in the solution before being captured. Assuming that the solution contains only nuclei which absorb neutrons according to the $1/v$ law (the only exception to this rule will presently be dealt with), τ is proportional to $1/\Sigma c_i\sigma_i$, where c_i is the concentration (atom grams per litre) of an absorbing nucleus, σ_i its cross-section for the capture of neutrons of velocity 1 and the index i is extended to all kinds of neutron-absorbing reactions attributable to nuclei present in the solution. Substituting the symbol A_i for $c_i\sigma_i$ and A_{tot} for ΣA_i, we have identically:

$$\frac{\Delta S}{S} = \frac{\Delta Q}{Q} - \frac{\Delta A_{tot}}{A_{tot}}, \qquad (1)$$

neglecting all terms of higher orders, such as those containing $(\Delta Q)^2$, $\Delta Q.\Delta A_{tot}$, etc.

Let the symbol Δ stand for the differences observed between the two solutions (uranyl and ammonium) used in our previous experiment[1]. Neglecting ΔA_{tot} before A_{tot} introduces an ambiguity in the definition of A_{tot} (uranyl *vs.* ammonium value) which is numerically unimportant and can be reduced by adopting the arithmetical mean $(A_{tot}(\text{amm.}) + \Delta A_{tot})/2$.

In the quantity ΔA_{tot} the uranium nuclei are represented by several separate terms standing for the different modes of neutron capture (see below); let A_f be the term for the capture leading to fission. Every neutron has the probability A_f/A_{tot} of causing a fission and, since one individual fission process liberates ν neutrons on the average, the total number ΔQ of neutrons thus created is $Q.\frac{A_f}{A_{tot}}.\nu$, and the equation (1) can be rewritten as follows:

$$\nu = \frac{\Delta S}{S} \cdot \frac{A_{tot}}{A_f} + \frac{\Delta A_{tot}}{A_f}. \qquad (2)$$

Let us estimate the values of all quantities necessary to calculate ν according to this formula. The area variation $\Delta S/S$ can be read from the graph given in our previous letter with an error of less than 20 per cent (due to the uncertainties of inter- and extrapolation; in order to facilitate the latter, we added to the curves a further experimental point for $r = 29$ cm.). The value of A_{tot} for the ammonium solution can be easily calculated from the known concentrations and capture cross-sections (hydrogen, nitrogen and oxygen). A_f is equal to c_U (1·6 in our experiment), multiplied by the value of σ_f given in a recent paper by Anderson *et al.*[4]. ΔA_{tot} contains a term expressing the small difference of the hydrogen content between the two solutions; and three terms relative to uranium, namely, the fission term A_f, already dealt with, the thermal capture term A_{ct} which can be calculated by using a recently found value for σ_{ct} [5] and finally the resonance capture term A_r which requires some explanation.

Our reasoning assumed that all neutrons introduced into the solution spend practically all their life, and are absorbed, in the thermal state. This is true in so far as the $1/v$ law is valid for absorption of neutrons in all nuclei concerned; and, therefore, not wholly true for uranium, which shows a pronounced resonance capture of neutrons of about 25 volts[6]. A certain proportion of neutrons entering the solution is bound to come within this resonance band and to be absorbed by resonance; therefore, it will never reach the thermal state. This proportion depends on the width of the resonance band and on the concentration c_U; its value in our system of symbols is equal to A_r/A_{tot} and was numerically determined by an experiment reported elsewhere[5].

Putting all numerical values in the formula (2) (with 10^{-24} cm.^{2} as the unit of cross-section), that is: $\Delta S/S = 0{\cdot}05 \pm 0{\cdot}01$; $A_{tot} = 36 \pm 3$; $A_f = 1{\cdot}6 \times 2 = 3{\cdot}2$; $\Delta A_{tot} = 8{\cdot}7 \pm 1{\cdot}4$ decomposable into $\Delta A_H = 1{\cdot}2 \pm 0{\cdot}1$, $A_{ct} = 1{\cdot}6 \times (1{\cdot}3 \pm 0{\cdot}45) = 2{\cdot}1 \pm 0{\cdot}7$, $A_r = 6{\cdot}4 \pm 1{\cdot}1$ and $A_f = 3{\cdot}2$, we find:

$$\nu = 3{\cdot}5 \pm 0{\cdot}7.$$

We were not able to allow for an error in A_f, since the value of σ_f given by Anderson *et al.* contains no indication of probable error. Any error in σ_f will affect $\nu - 1$ in an inversely proportional way; in any case ν will remain greater than 1.

The interest of the phenomenon discussed here as a means of producing a chain of nuclear reactions was already mentioned in our previous letter. Some further conclusions can now be drawn from the results reported here. Let us imagine a medium containing only uranium and nuclei the total neutron absorption of which, as compared to that of uranium, may be neglected (containing, for example, only some hydrogen for slowing down purposes). In such a medium, if $\frac{A_f}{A_{tot}} \cdot \nu > 1$ (A_{tot} includes now only uranium terms), the fission chain will perpetuate itself and break up only after reaching the walls limiting the medium. Our experimental results show that this condition will most probably be satisfied (the quantity $\frac{A_f}{A_{tot}} \cdot \nu - 1$, though positive, will be, however, small), especially if one keeps in view that the term A_r, because of the self-reversal of the resonance absorption line, increases much more slowly than the other uranium terms when the uranium content of the medium is increased.

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